Evolving Magnetic Structures and Their Relation to Coronal Mass Ejections

Joan Feynman
Jet Propulsion Laboratory
California Institute of Technology
Pasadena CA., 91109

AIMI.net: Solar activity regions are frequently concentrated into clusters which persist for many solar rotations. These activity complexes are associated with weak dispersed magnetic fields which are most apparent after the activity itself has ceased. We call this combination of persistent activity and dispersed fields Evolving Magnetic Structures (EMS). Here we show examples of EMSs and describe the evolution of an EMS associated with major Coronal Mass Ejections (CME) and other solar and magnetospheric disturbances. We show that CMEs occurred throughout the history of this EMS. We find that the time scale for important evolutionary changes in the EMS is about 3 to 6 weeks, i.e. about a complete solar rotation or more. Thus studies of individual EMSs require that each EMS be observed continuously for several weeks, necessitating observations of both sides of the Sun.

1. Introduction

Bumba and Howard (1965) studied the distribution of active regions and of weak magnetic fields on the Sun. They concluded that active regions were concentrated into complexes of activity associated with the development of large regions of dispersed magnetic fields. To emphasize the Close relation of the complexes of activity and the regions of dispersed fields we suggest that they be considered to be one entity which we call Evolving Magnetic Structures (EMS) (Feynman and Hundhausen, 1994). This name also emphasizes the fundamental magnetic and evolutionary nature of both phenomena. EMSs are probably closely related to the evolutionary structures described much earlier by Kiepenheuer (1953) from $H\alpha$ observations of sunspots and filaments.

He reported that in their early stages sunspots emerged and there were few if any filaments. Later, as more active regions emerged flaring occurred and filaments began to form, lengthen and rotate toward an east-west direction. in the final stage, several rotations later, the spots had all disappeared, flaring had ceased and (rely large scale quiescent filaments remained.

By now statistical studies of solar activity have demonstrated conclusively that solar activity and emerging solar flux are not distributed at random on the solar surface (Gaizauskas et al. 1983;

Brouwer and Zwaan, 1 990). Instead there is a strong tendency for the new flux to appear in certain regions. Magnetograms clearly show distinct patterns in the photospheric magnetic field that persist for many months (Gaisauskas et al, 19!33). 1 larvey and Zwaan (1 993) found that al. least 55% of all spots larger than 3.5 square degrees emerge as part of activity nests. New magnetic flux and sunspots emerge over and over again within these EMS patterns. Gaizaukas et al. (1983) gave an example of a pattern that lasted for 6 months and contained 29 major active regions. After several rotations the emergence of new sunspots may cease but dispersed magnetic fields may still be seen. Sometime.s, after one or two rotations with only dispersed fields, new sunspots again appear and flaring resumes. It has been proposed that the clustered sunspots may represent the submerged flux loop arches from which active regions repeatedly emerge (Zwaan and 1 larvey, 1994).

2. *A quiet Sun EMS*

Figure] shows an example of an EMS at solar minimum. Each **of** the six panels is a synoptic map of the. photospheric magnetic field intensity as measured by the National Solar Observatory at Kitt Peak. A synoptic map is produced from daily measurements by showing the magnetic flux at central meridian passage collected over the 27 days of the solar rotation. The figure is a grayscale presentation in which the flux is represented in a dark (field into the Sun) and light (field out of the Sun) scale. 1 ow field intensities appear as gray. The six panels of the figure show fields observed between the equator and a latitude of 40 degrees south during six successive. rotations of the Sun. Note that between 80 and 120 degrees solar longitude there is a structure in the magnetic field that returns with each rotation but evolves from one rotation to the next. Sunspots and newly emerging magnetic fields are observed in the first 3 or 4 rotations shown, but in the final rotation, only dispersed fields are seen. The magnetic field pattern has simplified and a magnetic neutral line is clearly seen. This is the type of magnetic field structure in which filaments fol'in.

3. *CMEs and EMSs*

CMEs are associated with major flares and with filament eruptions (Gosling et al., 1 974; Munro et al. 1 979; Webb and 1 lundhausen, 1 987). Likewise CMEs are associated with sheared magnetic fields and with the emergence of new magnetic flux (I 'eynman and Martin, 1995). in all cases, apparently the same type Of large-scale coronal structure is destabilized and leaves the Sun (Hundhausen, 1 994). Typical latitudinal widths of these structures are about 45 degrees (Burkepile and St. Cyr, 1 993), much larger than the. scale of the underlying flare or filament. It has been argued (1 'eynman and Martin, 1995) that,

with the. possible exception of the initial acceleration profile (MacQueen and Fisher, 1983), no cleat characteristic has been identified that distinguishes between CMEs associated with flares, and those associated with quiescent filament eruption, or magnetic shear or newly erupting flux. This suggests that all CMEs, whatever their association, are initiated within the same type of large-scale, well organized, magnetic field regions (Hundhausen, 1988; Feynman and Hundhausen, 1994). Since an EMS is a single entity that involves flaring, active regions and quiescent filaments, magnetic flux eruption and magnetic shearing, Feynman and Martin (1995) have suggested that CMEs take place during all stages of the evolution of the EMS and the CMEs are associated with flares or rising prominences (disappearing filaments), and erupting flux or shear depending on the stage of evolution of the EMS.

4. *An active Sun EMS*

In March 1989 an active region produced a series of a major CMEs, a large solar energetic proton event and a very intense geomagnetic storm (c. f. Feynman and Hundhausen, 1994 and references therein). The active region was a return of one that appeared on at least one previous solar rotation and reappeared on the following rotation (Joshi, 1993), thus qualifying it as an EMS. Here we describe the evolution of that EMS and its relation to CMEs throughout its evolution.

Figure 2 shows stacked synoptic maps from the North Solar Hemisphere from November, 1988 ((Barrington rotation 1809) through May, 1989 (rotation 1815). This was a very active period of the Sun and there were ninny EMS candidates. As in the case of the EMS shown in Figure 1, changes in each of the activity centers took place during a single rotation. At solar minimum it was simple to unambiguously identify the returns of the EMS because there was very little other activity. However, in Figure 2, although it is clear that activity centers return, it is sometimes difficult to choose among the possible recurrence s of a particular center. The region that produced the March events appears on the third strip from the bottom and at a solar longitude of about 250 degrees, Joshi (1993) has identified returns on the previous and the following rotation as shown between the white. lines in the figure. The data show evidence.that this EMS existed during three rotations before those identified by Joshi. The activity during the rotation after the March events (second strip from the bottom) was much diminished. On the next rotation only dispersed fields were seen. The rotation after that (not shown) also showed only dispersed fields.

The rotation rate of the 1 EMS was a little less than 27 days. This is in agreement with the findings of Gaizauskas et al. (1983) who reported that each 1 EMS has its own rotation rate.

4.1 Magnetic flux and flaring

EMS magnetic flux changes between returns and during disk passage. A rough estimate of the flux in a region can be obtained from the area of the sunspots. The areas are routinely determined each day from full disk observations. Figure 3 gives an indication of the flux history for this EMS. The figure gives an estimate of the area of the sunspots when the active region was al 60 degrees East and 60 degrees West. The East and West longitudes are chosen to be equal so that projection effects will not affect the relative flux determination. The sunspot areas are given in units of 10^{-6} of the visible solar hemisphere. The sunspot areas for the March rotation, the preceding 2 rotations, and the following rotation are shown in Figure 3. A solid line connecting points indicates that the region was on the. observable faccofthcSLm. If there is a dashed line the region was too close to the limb or on the far side of the Sun. In the discussion [hat follows the rotation in which the March events took place will be referred teas rotation (), the preceding rotations will be called -1, -2, etc. and the following rotations +1, +2 etc.

During rotation -2 the sunspot area increased from about 1 S() to about 1400" and the spot count increased from about 8 to 2"1. Remarkably, in spite of this large quantity of emerging flux, there was only one class M X-ray flare during that rotation. (X-ray events are classified as C, h4, and X, C indicates 10^{-6} w/m^{-2} and M and X are each one factor of 10 higher.)

By the time the EMS reappeared (rotation - 1) the area had further increased to about 1800" and there were about 32 spots. During rotation -1 nine X-ray flares of class M or above took place and both the' area and spot count decreased by about a factor of two. The 1 EMS appeared to be declining.

Although rotation -1 showed waning activity, by rotation () the area had recovered to 2000. Even before the spot group had come over the Eastern limb a series of high speed CMEs had begun (Feynman and Hundhausen, 1 994).

During the O disk passage the area reached 3000 and the sunspot number reached 50. The sunspot magnetic configuration was highly complex and Joshi (1993) classified the region as "superactive". The active region was the most prolific X-ray flare producer in the

preceding 15 years. There Were several spectacular sudden energetic solar events as the center of activity was carried across the face of the sun (Abbott et al., 1 993). These include a March 6 event during which the GOES X-ray monitors went off scale. This was estimated to be. a class X 15 event, the largest ever seen to that date, On March 9 a X4 event occurred. March 10 had an X4.6 event that caused the geomagnetic storm of March 13 which included the most disturbed 24 hour interval in 120 years (Allen c(al. 1989). *On* March 16 a 3B flare occurred accompanied by bright surges over 34 degrees in extent. All-together during disk passage 0 there were 35 class M flares and an additional *10 class X* events. At least *195* individual optical flares were observed. Three CMEs were observed (March 6, March 9, and March 17). The associated solar energetic particle event was the largest since]972. None of this activity could have, been predicted because the re-energization of the EMS took place while it was on the far side of the Sun.

When this EMS was at 60 degrees West and about to go over the limb its area was almost the same as it had been at central meridian passage. However, while it was unobserved, cm the far side of the Sun, the sunspot area and number declined precipitously. Only a small area (9 0) and a f c w spots (~3) wl iere present on the +1 return. It would have been extremely interesting to observe the phenomena associated with this precipitous decline of a "superactive" region.

Not unexpectedly, there were no sunspots during the -t 2 return. However a huge quiescent filament had developed. The filament channel included the neutral line of the dispersed fields but was much longer. The filament was over 160 degrees in longitude and over 60 degrees in latitude. During this disk passage a section of the filament erupted. A section also disappeared during rotation +3 (not shown).

4.2 CME history

Studies of the CME history of this EMS were hampered by the usual difficulty **that** CMEs are only visible when they occu r within 2.5 days of limb passage. Furthermore, CMEs are often not centered over the associated active region (Harrison and Sime, 1989). Table 1 lists CMEs that can be reasonably associated with the activity complex near the limb on the basis of the CME position and time of eruption. The data are from Burkepile and St.Cyr (1993). The table gives the. date of the CME and the latitude of its center. During four consecutive rotations (-3 to O) eight CMEs were observed at about the comet place and time. The East and West limb CMEs during rotation () have been described at length in the

literature (Feynman and Hundhausen, 1 994). The consistency of the. west limb position for four CMEs observed on three different rotations is remarkable. During the returns after rotation 0 no CMEs were seen when the active region would have been near the limb. However, since filament eruptions normally occur in association with CMEs (c.f. Feynman and Marlin, 1995), continuing CME activity can be implied from the two filament eruptions that occurred during rotations +2 and +3. Thus CME activity occurred during at least six relations of this EMS.

5. Future EMS studies · observational difficulties and their solutions

EMSs have typical lifetimes of 6 months or more during which they may repeatedly give rise to coronal mass ejections and have important solar-terrestrial effects. The extraordinary tendency for repeated flux emergence over such long time periods and the well ordered dispersed fields suggest that EMSs are fundamental entities for understanding the solar cycle and the solar dynamo. In the example studied here daily observations showed that the EMS flux built to a maximum while the region was on the far side of the Sun, major CMEs took place when the region was on this side Of the Sun and the region exhausted itself precipitously while on the far side of the Sun. These three important steps in the evolution, build up, CMEs and decline, took place during a period Of about one and a half solar rotations. Thus there is a serious observational difficulty. Assuming one and a half solar rotations is a typical time scale, not all of the crucial evolutionary steps for a single EMS can be observed. in the. case discussed here the buildup to maximum and the rapid decline where not actually Observed.

This observational problem has plagued studies of EMSs and contributed to the curious situation that, although EMSs appear to be fundamental to the operation of the solar dynamo, very little is known about them except that they exist and are common. Individual EMSs have lifetimes of many months and we have shown here that important evolutionary changes within them take place on time scales of weeks. Thus, if they are observed hourly or daily from only one side of the Sun, the evolutionary changes within any one individual evolving structure can not be satisfactorily followed. In fact, without observing the other side of the Sun, it is often difficult to determine whether or not an individual sunspot group appearing on the east limb is the return of a group last seen 13 days earlier disappearing over the west limb. Since these phenomena include some. of the most important entities for understanding the operation of the solar activity cycle, the initiation and acceleration of CMEs and forecasting and monitoring solar weather, it is vital that the handicap of single-solar-hemisphere observations be overcome.

The most straightforward way to accomplish this would be to station a spacecraft so that it views the other side of the Sun continuously. An orbit that accomplishes this has been identified. Data from the other side of the Sun (combined with whatever observations are taking place on this side. of the Sun) would allow the EMS to be observed 20 of the 27 days of a solar rotation. (During the other 7 days the. EMS would be too close to the limb.) Observations of EMSs would then be continuous enough to study the evolution of individual EMSs. Such observations would very much facilitate studies of the role EMSs play in the solar cycle and in the operation of the dynamo [Parker, 1 978; Zeldovich et al., 1983].

Table 1- Coronal Mass Ejections

Appearance number	East limb	West limb
-3	Dec. 9, N22 deg.	Dec. 27, N38 deg.
-2	Jan 7, N35 deg.	Dec. 23, N38 deg. Jan 21, N37 deg.
-1	Feb. 4, N48 deg.	none
0	March 6, N56 deg.	March 17, N38 deg.
+1	none	none
+2	filament section disappears, implying CME	
+3	filament section disappears, implying CME	

Figure captions:

Figure 1. Stacked synoptic maps of the photospheric magnetic field during solar minimum. The earliest rotation appears at the. top of the. figure, Latitudes between zero and forty degrees south are shown. An EMS is seen at about 90 degrees solar longitude. (data from NSO/Kitt Peak).

Figure 2. The same as figure 1 but for an active solar period. Latitudes shown are between 5 degrees south and 50 degrees north. The } EMS associated with the March 1989 events appears between the white lines. The active center associated with the March events themselves is seen in the third strip from the bottom.

Figure 3. An estimate of Sunspot area in the EMS during four returns. The time scale is in days, and the zero day is chosen to be the time when the region was at 60 degrees East on rotation -2. Two data points are given for each rotation , when the active region was 60 degrees East and West of central meridian passage.

References :

Abbott, M. S., et al., Region 5395: A harbinger of solar activity cycle 22, G. R. Heckman, M. S. Abbott, 1.. 1,. Orita and R. 1,. Bass, NOAA TMERL SEL., 1989.

Allen, J., }1. Sauer, L.. Frank, and P. Reiff, Effects of the March 1989 Solar Activity, EOS. Trans. of the AGU, 70, 1479, 1989.

Brouwer, M. P. and C. Zwaan, Sunspot nests as traced by a cluster analysis, Solar Phys., **129**, 221, 1990.

Bumba, V. and R, 1 loward, 1,argo-scale distribution of solar magnetic fields, Astrophys. J., **141**, 1502, 1965.

Burkepile, J. T. and O. C. St. Cyr, A revised and expanded catalogue of mass ejections observed by the Solar Maximum Mission Coronagraph, NCAR/TN-369+STR, NCAR, Boulder Colo., 1993.

Feynman J. and A. J. 1 lundhausen, Coronal mass ejections and major solar flares: the great active center of March 1989, J. Geophys. Res., 99, 8451, 1994

Feynman, J. and S. F. Martin, The initiation of corona] mass ejections by newly emerging magnetic flux, J. Geophys.Res., 100, 3355, 1995.

Gaizauskas, V., K. 1,. Harvey, J. W. Harvey and C. Zwaan, I ,al'ge-scale patterns formed by solar active regions during the ascending phase of cycle 21, Atrophys. J. 265, 1056, 1983.

Gosling, J. '1'., E. Hildner, R, M. MacQueen, R. H. Munro, A. I. Poland and C. 1,. Ross, Mass ejections from the sun: A view from Skylab, J. Geophys. Res. 79,4581, 1974.

Harrison, R. A. and D. G. Sime , The launch of corona] mass ejections : White light and X-ray observations in the low corona, J. Geophys. Res. 94, 2333,1989.

1 larvey, K.I, and Zwaan, C. Properties and emergence patterns of bipolar active regions: Size distributions and emergence frequencies, Solar Phys., 148, 85, 1993.

Hundhausen, A. J., The origin and propagation of corona] HMSScjcc[ions,p181, Proceedings of the Sixth International Solar Wind Conference, V. J. Pizzo, T. E. Holzer, and D. G. Sime, eds. NCAR/TN 306-1 Proc , 1 988.

Joshi, A., Superactive region AR 5395 of solar cycle 22, Solar Physics 147, 269, 1993

Kiepenheuer, K. ()., Solar Activity, p322, The Sun, G. P. Kuiper, ed, University of Chicago Press, Chicago Ill. 1953.

MacQueen, R. M. and R. R. Fisher, The kinematics of solar inner corona] transients, Solar Phys. 89, 89, 1983.

Munro, R. 11., J. T. Gosling, E. Hildner, R. h4. MacQueen, A. 1. Poland, C. I.. Ross, The association of coronal mass ejection transients with other forms of solar activity, Solar Physics, 61, 201, 1979.

Parker, E., Cosmic Magnetic Fields, Oxford Univ. Press., 1978

Webb, 1). F. and A, J. Hundhausen, Activity associated with the solar origin of coronal mass ejections, Solar Phys., 108, 353, 1987

Zeldovich, Ya, 11., A. A. Ruzmaikin, and D. D. Sokoloff, Magnetic Fields in A.v(]-oj)lly.vie:.v, Gordon and Breach, New-York, Paris, 1 .ondon, 1983.

Zwaan, C. and K. 1., Harvey, Patterns in the solar magnetic field, p27, in Solar Magnetic Fields, M, Schussler and W. Schmidt, eds., Cambridge University **Press, 1994**
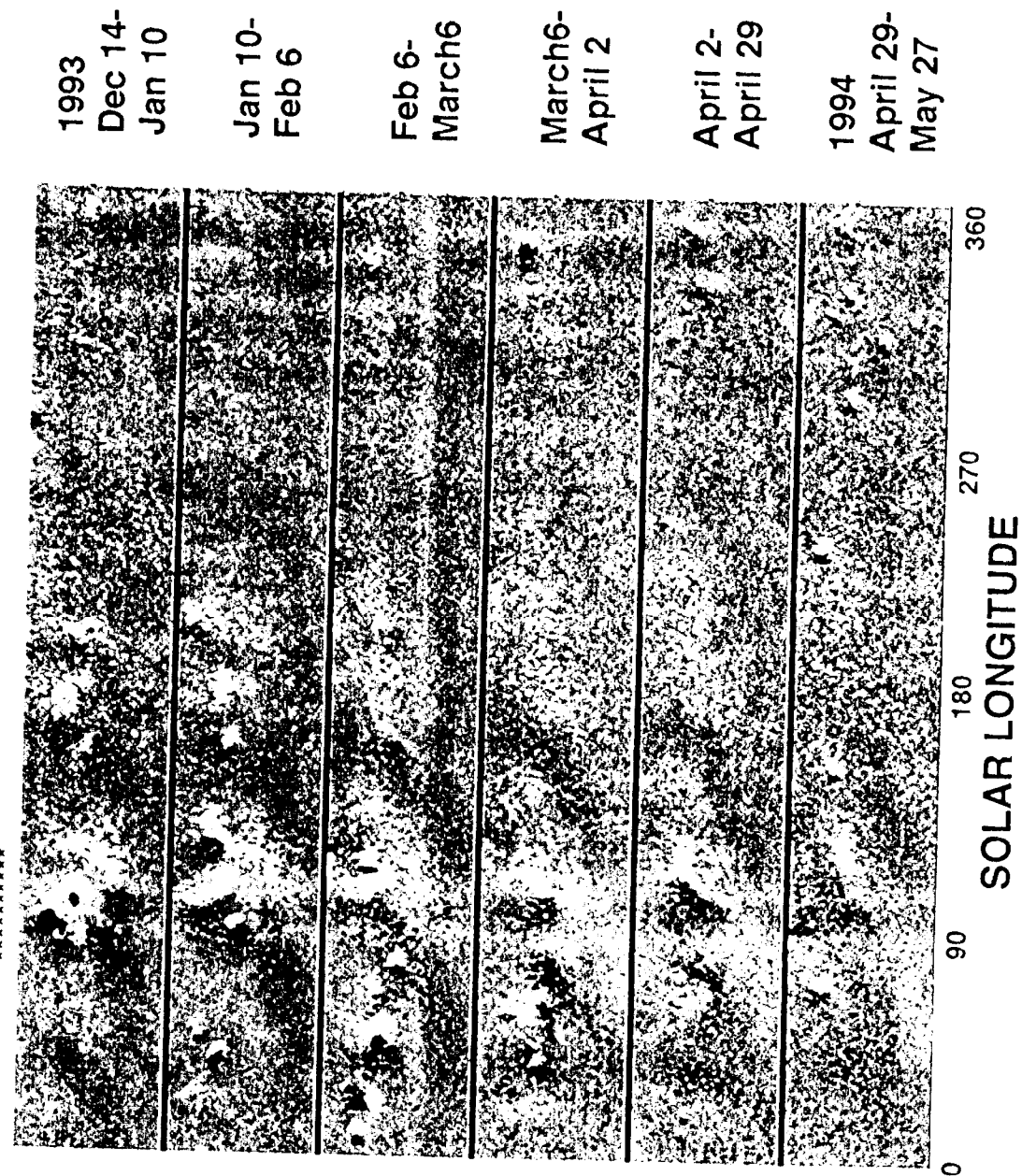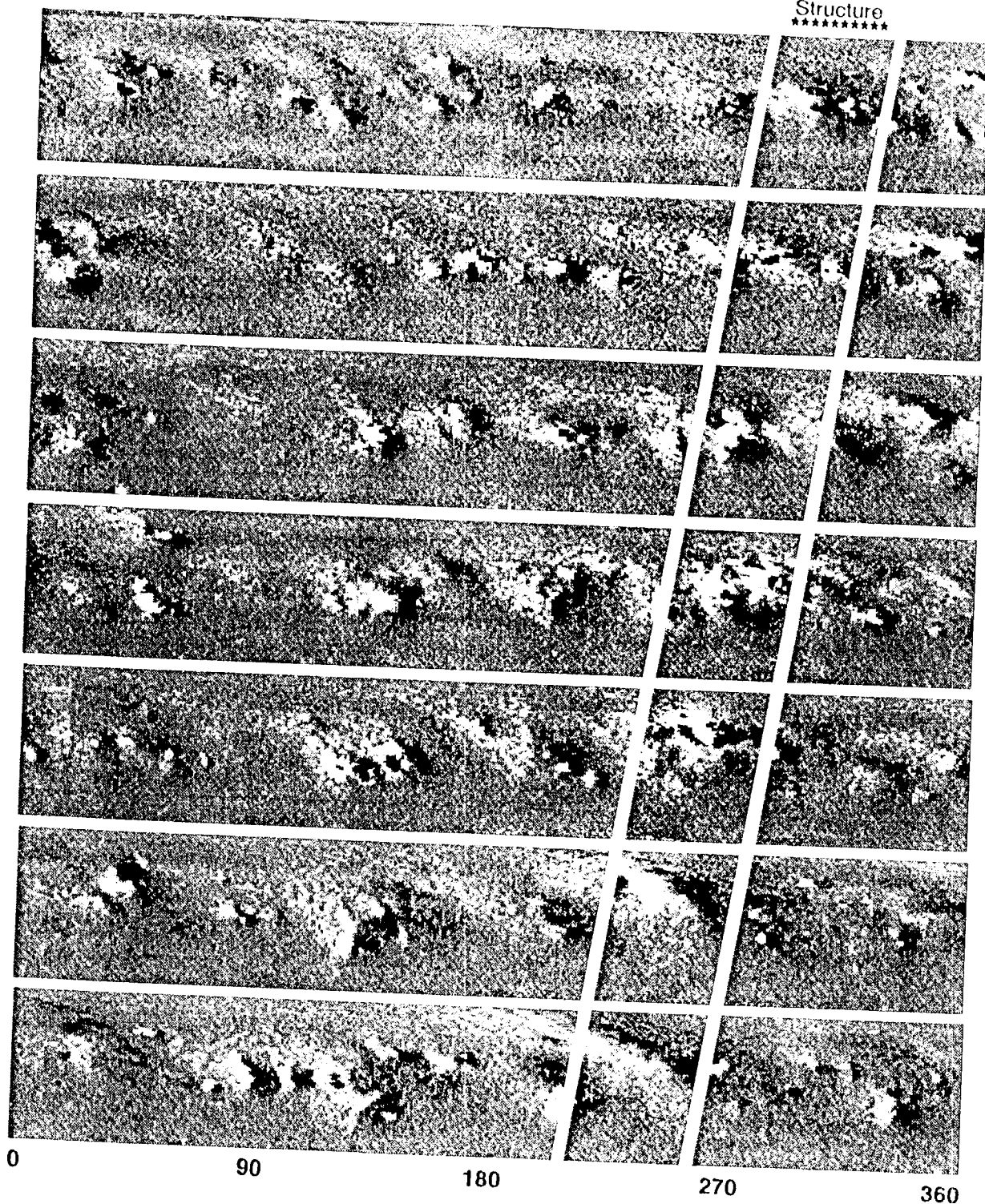
Fig.

Evolving Magnetic
Structure
★★★★★★★★★

0   90   180   270   360

SOLAR LONGITUDE

Area **of Sunspots** (January-April, **1989)**